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Biomass and carbon allocation within the Atlantic humid rainforest of southern Cameroon: Useful information for the implementation of REDD+ in Congo basin countries

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Abstract

This study is an evaluation of carbon pools in the southern forest of Cameroon. It provides useful information for the implementation of REDD+, which requires reliable forest carbon data and monitoring systems to reduce forest loss. Data on diameter measurements and wood density for trees above 10 cm Dbh was collected within 65 randomly distributed plots across three sites with varying degrees of disturbance severity. A total of 200 subplots were set-up to estimate stem biomass and 100 quadrats to collect litter and soil corer for the estimation of root biomass. Results showed an estimated wood density of 0.63 ± 0.15 $g.cm^{-3}$. High biomass and carbon values were observed in Campo (1170.63t/ha, 585.315tC/ha), as compared to Bidou (751.89 t/ha, 375.95 tC/ha) and Mangombe (571.34t/ha, 285.67tC/ha). There was a high biomass allocation ranging between 94.98% and 97.97% for standing trees. Conversely a low contribution of less than 7% was observed for small diameter trees (Dbh<20 cm), followed by fine roots (1.62 - 3.82%) and litter (0.34 - 0.94%). Variation in biomass can be explained by the level of disturbance, heterogeneity in the spatial distribution of forest types, absence of standardized sampling rate and allometric equations for the Congo basin forest. Due to the complexities involved in forest biomass inventories and the low contribution of small diameter trees to the total biomass, the study suggests that trees with Dbh < 20 cm can be neglected.

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Introduction

The Congo Basin forest accounts for 15% of the world's forest carbon stock, but available information on this parameter is less reliable and often difficult to access (Laporte *et al.*, 2008). To generate carbon credits under the REDD+ program, accurate estimates of forest carbon stocks are needed. Carbon accounting efforts focus on carbon stocks in aboveground biomass (AGB) while limited information is available on the contribution of the belowground compartment, especially for the Atlantic rain forest, which is known as a biodiversity hotspot (Myers *et al.,* 2000; Tchouto, 2006). Above and below ground biomass plays a key role in climatic changes as well as in biochemical and geochemical cycles. It determines the amount of carbon which can be captured in the atmosphere by plants and makes it possible to estimate the carbon potential which can be released in the atmosphere in case of deforestation.

Biomass is used in the characterization of the structure and function of forests. It is an ecological indicator of the sustainable management of forests and a tool for the implementation of Reduction of Emissions through Deforestation and Degradation of forests (REDD+) mechanism (Djomo *et al.*, 2010; 2011; Sishir and Stephan, 2012). Despite the importance of roots for water, nutrient uptake, carbon, nutrient and water cycling at the plant and ecosystem levels, the difficulties associated with their sampling and evaluation result in a lack of information for different environments (Leuschner et al., 2007, Graefe et al., 2008). Meanwhile, this data is essential to parameterize models about ecosystem functioning and response of plants to changes in climate (Rosado et al., 2011).

The Kyoto accord recommends the estimation of carbon potential during floristic inventory activities (Pignard et al., 2000). Unfortunately, most inventories carried out within the Congo basin forests do not consider tree biomass. Consequently, its carbon potential and information on root biomass remain scarce and unreliable due to the limitations of measuring methods. Thus, uncertainties remain on the quantitative contribution of the rain forest compartment to the global carbon cycle (Chave *et al.*, 2005). This study seeks to contribute to the understanding and improvement of knowledge on forest carbon pool biomass, by using different levels of disturbance to investigate the aboveground biomass (AGB), belowground biomass (BGB), litter and roots in three sites of the dense Atlantic humid forest.

Materials and methods

Study area

This study was carried-out within the low land dense humid forest of southern Cameroon, subdivided into three sites characterized by varying degrees of disturbance severity. The three sites were: Campo Ma'an National Park (2°21'N and 10°06'E, a mature forest), Mount Elephant Forest at Bidou (2°48'N and 10°01'E, an old secondary forest) and Mangombe Forest (3°50'N and 10°10'E, a young secondary forest). Mean annual rainfall within the three sites ranges between 2800 and 2950mm, and mean annual temperature is between 24 and 33°C. The vegetation is dominated by *Lophira alata* Banks ex P. Gaertn (Azobé, Ochnaceae)*, Sacoglottis gabonensis* (Baill.) Urb. (Bidou, Humiriaceae)*, Cynometra hankei* Harms (Nkokam, Caesalpiniaoideae) and *Coula edulis* Baill. (Ewomè, Olacaceae) (Fig. 1) (Letouzey, 1957 ; Ntabe *et al.*, 2012).

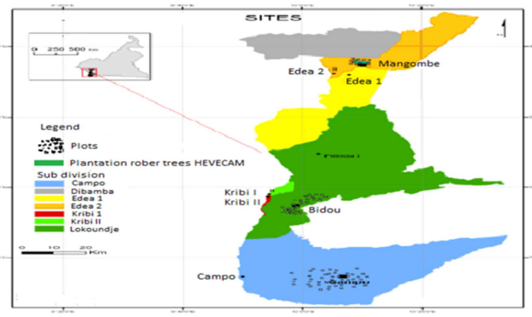

Fig. 1. Geographic situation of Mangombe, Bidou and Campo forest stations in South Cameroon

Estimation of tree biomass (Dbh ≥ 10 cm) using an allometric equation

Sixty-five plots of 20m × 20m each were randomly set-up in each site to ensure a representative floral distribution. All trees with Dbh ≥ 10cm were counted, marked, identified and their diameters recorded. Dbh was used to estimate tree biomass using an allometric equation derived from Chave *et al.* (2005). The equation is based on a sample of 2410 trees from 27 sites of pantropical forests where 5cm<Dbh<156 cm and where the rainfall index varies from 1500 - 3500 mm/year.

It is given by the expression:

$Y = S*\exp(-1.499 + 2.1481 \ln(D) + 0.207 (\ln(D))^2 - 0.0281 (\ln(D))^3)$

Where

Y = Biomass (kg/tree)

D = Diameter (cm) and

S = Wood density.

Wood density of each species was estimated using a pylodin. For every tree, three measurements were taken at equidistant heights. The mean value that was obtained for individuals within each species was calibrated using the equation:

$D = 0.0134 + 0.800x$

Where

D = Density and

x = measured data, representing wood density of the species.

Carbon stocks were estimated at 50% of dry weight biomass (Ziter *et al.*, 2013).

Estimation of stem biomass (Dbh < 10 cm) by the destructive method

A total of 20 out of 65 plots were randomly selected at the different sites and 10 subplots of 1m² each installed in each selected plot. This gave a total of 200 subplots with an overall surface area of 200m² per site. Within the subplots, all stems with Dbh < 10cm were felled at ground level, collected, weighed and dried at 30°C until constant weight for dry biomass was reached.

Estimation of the litter biomass

Within the 20 selected plots per site, 5 subplots were chosen and 100 quadrats of 0.5m x 0.5m, covering 25m² each were installed for the collection of litter (dead leaves, branches, barks and fruits). The collected litter was weighed and dried at 30°C until constant weight for dry biomass was obtained.

Estimation of root biomass

In each of the 100 quadrats per site, a soil corer (20cm x 20cm) was used to collect samples at 0 - 20, 20 - 40 and 40 - 60cm. This corresponded to a combined surface area of 4m² and 2.4 m3 of ground. Soil from each layer was kept in separate bags and later taken to a stream for the extraction of roots by washing and sieving (2mm), Rosado (2011). Roots from each layer were enveloped, labeled and oven-dried at 30°C to obtain constant weight. The dried samples were weighed using a scale of 0.01g precision to determine dry biomass. The sum of biomass from different forest compartments (aboveground: trees, shrubs, litter and belowground: roots) represented the total forest biomass.

Results

Floristic composition

Out of the 195 sampling plots (65 plots/site), a total of 4921 trees were investigated. They were composed of 45 families (Bidou 34, Campo 31, Mangombe 40) and 130 species (Bidou 88, Campo 75, Mangombe 92). In terms of abundance and distribution, Fabaceae was the highest with 833 individuals estimated at 17% of the investigated trees and 24 species. In this group the subfamilly Ceasalpinioideae represented 13,80%; followed by Mimosoideae (2,6%) and Faboideae (0,57%). In all 3 sites, *Keayodendron bridelioides* (5.20%) was the most abundant species while in Mangombe, it was *Strombosia scheffleri* (7.88%), Bidou (*Dialium guineense*, 8%) and Campo (*Keayodendron bridelioides* 10.55%).

Wood density

Results showed a mean wood density of 0.61 ± 0.14 gcm^{-3} in Mangombe, 0.63 ± 0.15 gcm^{-3} in Campo and 0.65 ± 0.15 gcm^{-3} at Bidou. These corresponded to a mean density of 0.63 ± 0.15 gcm^{-3} for the study area. Results also revealed that wood density class 0.45 – 0.65 $g.cm^{-3}$ was more abundant and diversified. It was composed of 756 trees (51.92%) made-up of 56 species (63.63% of species richness) in Bidou; 927 trees (60.40%) composed of 45 species (59.21%) in Campo, and 1336 trees (69.26%) with 70 species (76.1%) in Mangombe. This class (0.45 – 0.65 $g.cm^{-3}$) had a total of 2840 trees (57.72%) from 87 species (67%) within the whole forest (Table 1 & 4).

Table 1. Estimated mean wood density of tree species and families

Family	Species	Species Wood Density	Family Wood Density
Anacardiaceae	*Pseudospondias longifolia*	0.46	0.46
	Trichoscypha ferruginea	0.46	
Anisophylleaceae	*Poga oleosa*	0.36	0.36
Annonaceae	*Cleistopholis patens*	0.34	0.44
	Enantia chlorantha	0.35	
	Pachypodanthium staudtii	0.46	
	Polyalthia suaveolens	0.46	
	Popowia sp.	0.46	
	Xylopia aethiopica	0.41	
	Xylopia quintasii	0.73	
Apocynaceae	*Alstonia boonei*	0.46	0.46
	Alstonia congensis	0.28	
	Funtumia africana	0.46	
	Funtumia elastica	0.46	
	Picralima nitida	0.46	
	Rauvolfia vomitoria	0.46	
	Tabernaemontana crassa	0.46	
	Tabernaemontana pachysiphon	0.46	
	Voacanga africana	0.46	
Aracaceae	*Elaeis guineensis*	0.46	0.46
Bignoniaceae	*Markhamia lutea*	0.46	0.37
	Markhamia tomentosa	0.46	
	Spathodea campanulata	0.33	
Bombacaceae	*Ceiba pentandra*	0.24	0.24
Burseraceae	*Aucoumea klaineana*	0.37	0.45
	Canarium schweinfurthii	0.30	
	Dacryodes buettneri	0.46	
	Dacryodes klaineana	0.46	
	Dacryodes macrophylla	0.46	
Caesalpiniaceae	*Afzelia africana*	0.65	0.56
	Afzelia bipindensis	0.67	
	Afzelia pachyloba	0.46	
	Anthonotha fragrans	0.64	
	Anthonotha macrophylla	0.46	
	Cynometra hankei	0.46	
	Detarium microcarpum	0.46	
	Dialium guineense	0.72	
	Dialium pachyphyllum	0.68	
	Didelotia africana	0.46	
	Distemonanthus benthamianus	0.52	
	Erythrophleum suaveolens (Guill. & Perr.)	0.59	
	Guibourtia tessmannii	0.46	
	Monopetalanthus heitzii	0.29	
	Pachyelasma tessmanii	0.46	
	Plagiosiphon sp	0.46	
Capparidaceae	*Bulchholzia coriaceae*	0.46	0.46
Cecropiaceae	*Musanga cecropioïdes*	0.20	0.20
Chrysobalanaceae	*Dactyladenia eketensis*	0.46	0.46
	Maranthes gabunensis	0.46	
	Maranthes kerstingii	0.46	
Clusiaceae	*Allanblackia floribunda*	0.64	0.58
	Garcinia manii	0.46	
	Symphonia globulifera	0.57	
Combretaceae	*Terminalia superba*	0.46	0.46
Ebenaceae	*Diospyros crassiflora*	0.67	0.69
	Diospyros kamerunensis	0.73	
Euphorbiaceae	*Alchornea cordifolia*	0.46	0.48
	Antidesma laciniatum	0.46	
	Drypetes gossweileri	0.57	
	Keayodendron bridelioides	0.46	
	Macaranga hurifolia	0.33	
	Manniophyton fulvum	0.46	
	Margaritaria discoidea	0.46	

	Plagiostyles africana	0.46	
	Uapaca guineensis	0.60	
Fabaceae	*Baphia leptobotrys*	0.46	0.50
	Pterocarpus soyauxii	0.50	
Flacourtiaceae	*Oncoba glauca*	0.46	0.46
	Scottellia sp.	0.46	
Humiriaceae	*Sacoglottis gabonensis* (Baill.) Urb	0.61	0.61
Icacinaceae	*Lavigeria macrocarpa*	0.46	0.46
Irvingiaceae	*Desbordesia glaucescens*	0.73	0.66
	Irvingia gabonensis	0.58	
	Klainedoxa gabonensis	0.77	
Lecythidaceae	*Petersianthus macrocarpus*	0.59	0.59
Loganiaceae	*Anthocleista nobilis*	0.46	0.46
	Anthocleista schweinfurthii	0.46	
Malvaceae	*Holea* sp.	0.46	0.46
Meliaceae	*Entandrophragma cylindricum*	0.53	0.43
	Entandrophragma utile	0.46	
	Khaya ivorensis	0.44	
	Lovoa trichilioïdes	0.37	
Mimosaceae	*Calpocalyx dinklagei*	0.54	0.61
	Cylicodiscus gabunensis	0.59	
	Entada gigas	0.46	
	Parkia bicolor	0.46	
	Pentaclethra macrophylla	0.73	
	Piptadeniastrum africanum	0.56	
Moraceae	*Antiaris toxicaria*	0.46	0.42
	Chlorophora excelsa	0.46	
	Milicia excelsa	0.46	
	Musanga cecropioïdes	0.20	
	Neosloetiopsis kamerunnensis	0.46	
Myristicaceae	*Pycnanthus angolensis*	0.40	0.48
	Staudtia kamerunensis	0.61	
Ochnaceae	*Lophira alata*	0.71	0.71
Oileniaceae	*Tetracera* sp.	0.46	0.46
Olacaceae	*Coula edulis*	0.73	0.58
	Ongokea gore	0.72	
	Strombosia grandifolia	0.59	
	Strombosia pustulata	0.46	
	Strombosia scheffleri	0.46	
Pandaceae	*Panda oleosa*	0.46	0.46
Passifloraceae	*Barteria fistulosa*	0.46	0.46
Rhamnaceae	*Maesopsis eminii*	0.35	0.35
Rubiaceae	*Aoranthe cladantha*	0.46	0.47
	Hallea ledermannii	0.46	
	Hallea stipulosa	0.44	
	Mitragyna ciliata	0.43	
	Morinda lucida	0.46	
	Nauclea diderrichii	0.64	
Rutaceae	*Zanthoxylum gilletii*	0.46	0.46
	Zanthoxylum heitzii	0.46	
Sapindaceae	*Ganophyllum giganteum*	0.46	0.46
Sapotaceae	*Baillonella toxisperma*	0.57	0.51
	Gambeya sp.	0.46	
	Omphalocarpum procerum	0.46	
Simaroubaceae	*Odyendyea gabonensis*	0.46	0.46
Sterculiaceae	*Cola acuminata*	0.49	0.48
	Cola argentea	0.46	
	Cola ficifolia	0.46	
	Cola gigantea	0.46	
	Cola nitida	0.69	
	Eribroma oblonga	0.46	
	Leptonychia sp	0.46	
	Triplochiton scleroxylon	0.30	
Tiliaceae	*Duboscia macrocarpa*	0.46	0.46

Table 2. Aboveground biomass (Dbh ≥ 10cm) in Bidou, Campo and Mangombe forest stations

Forest station	N (trees/ha)	Wood density (gcm^{-3})	Diameter (cm)	Biomass (t/ha)	Carbon (tC/ha)
Bidou	560	0.65 ± 0.15	10 – 238.73	717.61	358.81
Campo	590	0.63 ± 0.15	10 – 382.23	1146.89	573.45
Mangombe	742	0.61 ± 0.14	10 – 373.06	542.68	271.34

Table 3. Biomass of forest compartments (trees, litter, roots) that were investigated in Bidou, Campo and Mangombe forest stations

Forest compartment		Bidou		Campo		Mangombe	
		t/ha	%	t/ha	%	t/ha	%
Aboveground	Trees (Dbh ≥ 10 cm)	717.61	95.44	1146.89	97.97	542.68	94.98
	Shrubs (Dbh < 10 cm)	1.12	0.15	0.71	0.06	2.36	0.41
	Litter	7.1	0.94	4.02	0.34	4.48	0.78
Belowground	Fine roots	26.06	3.47	19.01	1.62	21.82	3.82
Total Biomass (t/ha)		751.89	100	1170.63	100	571.34	100
Total Carbon (tC/ha)		375.945	100	585.315	100	285.67	100

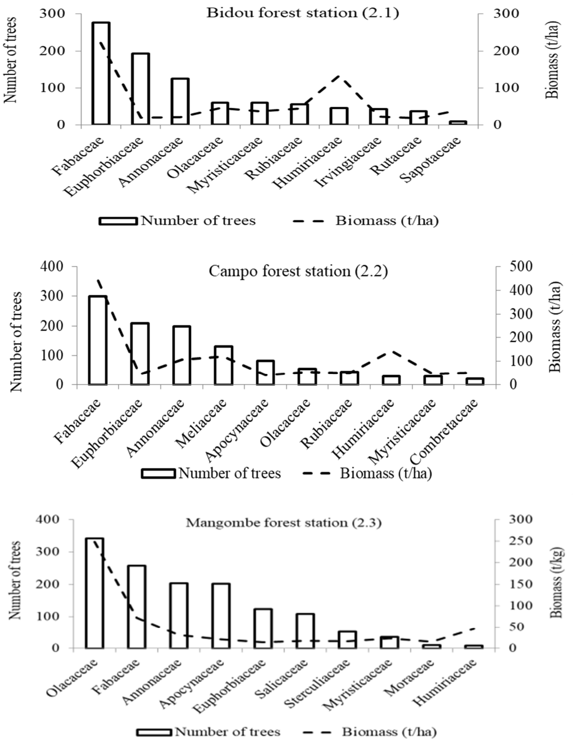

Fig. 2. Taxonomic distribution of tree biomass in Bidou, Campo and Mangombe forest stations

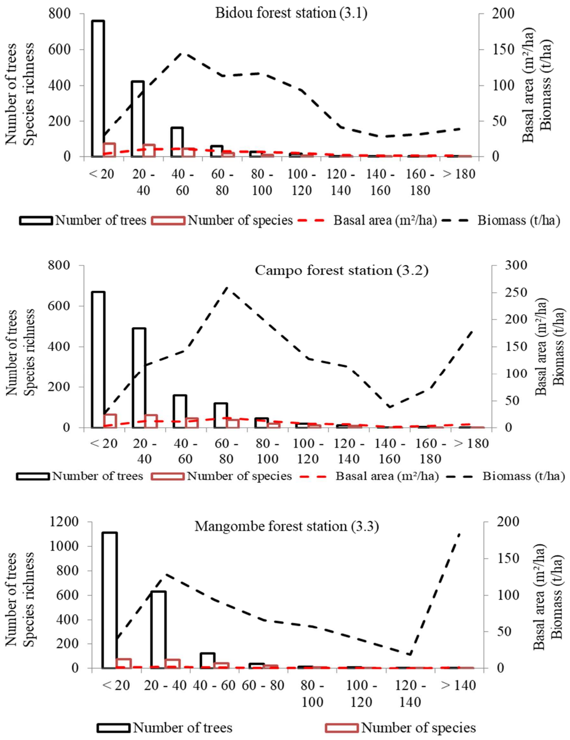

Fig. 3. Distribution of biomass (t/ha), species richness and basal area (m²/ha) according to diameter class

Aboveground biomass

Tree biomass with Dbh ≥ 10 cm

Tree biomass and stocked carbon were higher in Campo (1146.89t/ha; 573.45tC/ha) when compared to Bidou (717.61t/ha; 358.81tC/ha) and Mangombe (542.68t/ha; 271.34t/ha). The spread of the different diameter classes was observed in all three sites and the presence of emerging species with large buttresses justified the high biomass value that was observed in Campo (Table 2).

Taxonomic distribution of aboveground biomass (Dbh ≥ 10 cm)

Fabaceae was observed as the predominant family in the area with the highest biomass production of 221.84t/ha (30.91%) in Bidou and 441.83t/ha (38.52%) in Campo. Contrary to Bidou and Campo, the floristic composition in Mangombe was dominated by Olacaceae with a biomass production of 248.47t/ha, representing 45.78%. Other families such as Humiriaceae in Bidou and Campo and Myristicaceae in Mangombe were less invasive with few stands of *Sacoglottis gabonensis* (Humiriaceae) that increased AGB as well as Euphorbiaceae and Annonaceae with low biomass production due to their small size that constituted the undergrowth species (Fig. 2).

Distribution of biomass, specific richness and basal area within diameter classes

In each of the forest stations, the first diameter class (Dbh < 20cm) was the most diverse and the most abundant. It was mostly composed of smaller trees with lower biomass production potentials (< 7%) in each site. Diameter class 20-60cm constituted medium-sized stems with the highest biomass due to their population. We also observed that large diameter classes (Dbh ≥ 100 cm) with only a few emerging trees had a high biomass production estimated at 31.82% in Bidou, 38.29% in Mangombe and 41.74% in Campo. This result reveals that small size trees (Dbh < 20 cm) which are often neglected when estimating forest biomass can play a significant role in the estimation of biomass production (Fig. 3).

Biomass of litter and stems (Dbh < 10 cm)

The litter biomass was respectively estimated at 4.02t/ha in Campo, 4.48t/ha in Mangombe and 7.10t/ha in Bidou. It however varied considerably with the phenological stage of trees such as leaflessness, foliage and decomposition. The biomass of undergrowth stems (Dbh < 10cm) was higher in Mangombe (2.36t/ha) as compared to Bidou (1.12t/ha) and Campo (0.71t/ha). This situation can be justified by the dynamism of tree regeneration in the Mangombe undergrowth (708 stems/ha) compared to Bidou (538 stems/ha) and Campo (569 stems/ha). It is the result of recurrent human disturbances in Mangombe as compared to Bidou. No evidence of human disturbance was observed in Campo and this explains why the site was more stable. In all three sites, the performance of litter biomass production was greater than that of understory trees (Dbh <10 cm).

Table 4. Estimated average density of wood for tropical tree species

Zones	Sources	Mean Wood density ($g.cm^{-3}$)	Density variation ($g.cm^{-3}$)
Mangombe (Cameroon)	Studied site	0.61 ± 0.14	0.23 – 0.90
Bidou (Cameroon)		0.65 ± 0.15	0.23 – 0.95
Campo (Cameroon)		0.63 ± 0.15	0.23 – 0.95
Africa	Brown (1997)	0.56	0.50 – 0.79
America	Chave *et al.* (2008)	0.60	0.50 – 0.69
Asia	Gerard *et al.* (2009)	0.57	0.40 – 0.69
Dja Biosphere Reserve (Cameroon)	Djuikouo *et al.* (2010)	0.60 ± 0.15	0.50 – 0.79
Campo- South Cameroon	Djomo *et al.* (2010)	/	0.26 – 0.92

Table 5. Biomass values in some tropical rainforests (1-Ibrahima *et al.* 2002; 2- Sonwa, 2004; 3- Rees, 1963; 4- FAO/UNDP, 1972; 5- Jancovic, 1969; 1972; 6- Medina *et* Cuevas, 1989; 7- Russell, 1983; 8- Poels, 1987; 9- Sishir *et al.*, 2012)

Code	Pays	Type of forest	Biomass (t/ha)	Carbon (tC/ha)
Studied site	Cameroon	Mangombe (Young Secondary Forest)	657.04	328.52
		Bidou (Old Secodary Forest)	767.7	383.85
		Campo (Mature forest)	1291.61	645.81
1		Dense humid forest, Ebom	581	290.5
2		Cocoa- Agroforest	243	121.5
3	Guyanna	Primary forest	254	127
		Exploited forest	190	95
4	Nicaragua	Mature forest	240	120
		Secondary forest	183	91.5
5	Peru	Primary forest	210	105
		Secondary forest	192	96
		Secondary forest	125	62.5
6	Venezuela	/	301	150.5
7	Brasil		541	270.5
8	Surinam	/	542	271
9	Gabon	Dense humid forest (National Park of Mount Birougou)	302 ± 122	146 ± 58

Table 6. Root biomass in some tropical rainforests (1-Klinge *et al.,* 1975; 2-Klinge, 1976; 3-Grubb *et al.*, 1982; 4-Russel, 1983; 5-Poels, 1987; 6- Jordan, 1985; 7-Ibrahima *et al.*, 2002; 8-Sonwa, 2004; 9- Rosado, 2011; 10-Leuschner *et al.*, 2007)

Sites	Biomass (t/ha)	Sites	Biomass (t/ha)
Mangombe- Cameroon (Young secondary forest)	21.82	Brasil (Tropical humid forest)[4]	66.22-108.2
Mangombe- Cameroon (Tree plantation)	24.76	Surinam (tropical forest)[5]	127.74
Bidou- Cameroon (Old secondary forest)	26.06	Costa Rica[6]	14.4
Campo- Cameroon (Mature forest)	19.01	Cameroon-Ebom[7]	9.62 - 30
Venezuela[1]	56	Cameroon- Agroforest-cacao[8]	18
Brasil[2]	32.2	Serra do Mar State Park-Brasil (Lowland and montane forest)[9]	2.19-8.75
New Guinee[3]	40	Tropical forest[10]	1.50 - 11

Biomass of root and fine root

Results of the estimation of root biomass for 60cm deep profiles at all sites showed a total of 21.82t/ha in Mangombe, 26.06t/ha in Bidou and 19.01t/ha in Campo. A considerable decrease was observed with increase in depth. It was estimated in Mangombe at 16.38t/ha between 0 and 20cm depth, 4.31t/ha between 20 and 40cm and at 1.13t/ha between 40 to 60cm. In Bidou, it was 16.5t/ha, 7t/ha and 2.56t/ha respectively and 12.13t/ha, 4.63t/ha and 2.25t/ha in Campo (Fig. 4, Table 6). Root biomass between 0 to 60cm depth followed an exponential parabolic decreasing equation in all the sites where:

$Y_{Mangombe} = 62.40e^{-1.33X}$ ($R^2 = 1$); $Y_{Bidou} = 42.93e^{-0.93X}$ ($R^2 = 0.99$) and $Y_{Campo} = 27.05e^{-0.84X}$ ($R^2 = 0.99$)

Where,

Y = Biomass in t/ha and

X = Depth in cm.

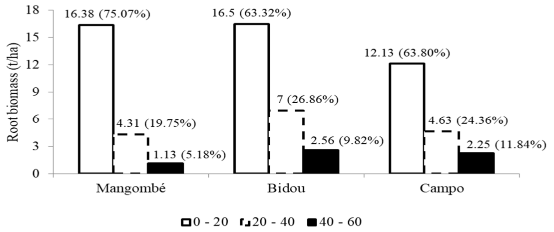

Fig. 4. Variation of root and fine root biomass with depth gradient at the forest Stations

Total forest biomass and carbon

The total biomass and carbon stored in the different forest compartments is contained in Table 3 & 5. The values were high in Campo forest station (1170.63t/ha, 585.315tC/ha), average in Bidou (751.89t/ha, 375.95tC/ha) and relatively low in Mangombe (571.34t/ha, 285.67tC/ha). Biomass distribution in the different compartments showed high values for trees with Dbh ≥ 10cm estimated at 94.98% - 97.97% of the forest station biomass, followed by roots and fine roots (1.62 - 3.82%), litter (0.34 - 0.94%) and undergrowth stems (Dbh <10cm) (0.06 - 0.41%).

Discussion

Wood density

The average wood density that was obtained in this study (0.63 ± 0.15 g.cm^{-3}) is close to the 0.60gcm^{-3} that was obtained in the Dja Biosphere Reserve in Cameroon (Djuikouo *et al.*, 2010) and Tropical African Forest (Brown, 1997). In the Congo Basin, Munier *et al.* (2009) indicate a wood density of 0.55gcm^{-3} with extreme values ranging from 0.49 to 0.61gcm^{-3}. The wood density class of 0.45 - 0. 65g.cm^{-3} is the most abundant and most diverse in all the stations. This observation is in the same increasing order (0.50 and 0. 79g.cm^{-3}) obtained by Chave *et al.*; (2003) in Panama.

Biomass accumulation

The observed biomass value in Campo is about 4 times higher than the overall average value of the tropical moist forests of America (169.7t/ha), Africa (260t/ha) and Asia (214.7t/ha) (Brown *et al.*, 1989). Other authors estimate biomass in African forests at 250t/ha (Nykvist, 1998) or 152 - 596t/ha (Brown & Lugo, 1984; 1992, Brown, Gillespie & Lugo, 1989, Clark *et al.*, 2001, FAO, 2007; Ramankutty *et al.*, 2007, Saatchi *et al.*, 2011). This gap can be explained by the fact that most studies don't take into account some biomass components like: litter, undergrowth and root biomass. However, these values are indicative of a high heterogeneous spatial distribution of carbon stocks.

The Campo site is rich in Humiriaceae and Fabaceae, composed of dominant species like *Sacoglottis gabonensis* and *Erythrophleum suaveolens*. Some trees belonging to these families have exceptional diameters (238.7cm ≤ Dbh ≤ 382.22cm) bigger than those used by Chave *et al.*, (2005) to develop biomass prediction equations. The regression models developed for biomass estimation are generally based on trees with small diameters. This explains why two models constructed for the same forest are likely to produce different biomass values (Nelson *et al.*, 1999, Houghton *et al.*, 2001, Chave *et al.*, 2004, Ntabe *et al.*, 2012). It is also necessary to consider the contribution of other forest compartments (roots, litter, and undergrowth) which significantly increase the biomass of the study area. Munier *et al.*, (2009) observed high variability in carbon stocks after the study of 4.8 million hectares of Congo Basin forest. This variability of forest biomass can be induced by several factors: forest types and level of disturbance due to variation of deforestation and forest degradation at spatial level, heterogeneity in the spatial distribution of forest types, absence of standardized sampling rate and allometric equations (Chave *et al.*, 2003, 2005; Duveiller *et al.*, 2008; Sishir *et al.*, 2012).

In order to develop a biomass prediction equation, increasing large trees in the sample will improve the coefficient of determination and reduce error margin. Meanwhile, forest inventories and field measurements have undeniable advantages in estimating carbon stocks. They provide accurate estimates that can detect spatio-temporal variations on a small scale and information on the impact of human activities on carbon stock changes. They can also help to test and calibrate measurement techniques based on satellite image analysis for large-scale carbon stock mappings. The limitations of this method, however, rely on the difficulties of stratification and sampling, field work constraints, associated high costs as well as data quality control. In Central Africa, there is great disparity in national and eco-climatic forest cover, and in Cameroon, almost all permanent plots are located in lowland dense humid forest (Picard, 2007).

Several studies have attempted to estimate tree biomass by integrating various parameters (diameter, height, and wood density) into the prediction equations (Quirine *et al.*, 2001; Chave *et al.*, 2005; Djomo *et al.*, 2010). Nelson *et al.* (1999), observed a 19.8% error in total biomass while using an allometric equation with diameter as the only variable from a sample of 132 trees in central Amazonia. Taking into account two variables (diameter and height) allowed only a slight improvement in accuracy, with a slight decrease in the average error (17.7%); while taking into account three variables (diameter, height and wood density) significantly improved the accuracy with an error of 14%. Similarly, Overman *et al.* (1994), on a sample of 54 Amazon rainforest trees, found an error of 25.6% on the biomass estimate using allometric equation with diameter as the only variable. Taking into account height in the equation, it was reduced to 24.3%, while the consideration of three variables (diameter, height and wood density) further reduced error to 11.2%. A similar observation was made by Djomo *et al.* (2010) in the dense humid forest of southern Cameroon, which recorded a reduction in woody biomass estimation errors from 7.4% to 3.4% when the number of variables was increased to three (diameter, height and wood density).

Distribution of biomass according to taxa and diameter classes

Small trees (Dbh < 10cm) and 7% (Dbh < 20cm) represent less than 0.5% of the total biomass of each station. Lescure *et al.*, (1983) and Chave *et al.* (2001) observed in the forest station of Saint Elie in French Guiana that small diameter classes have little contribution to the phytomass estimated at 2.5% (Dbh <10cm) and only 10% (Dbh < 20cm). From these observations, we can conclude that the minimum tree diameter that should be considered during biomass measurement inventories should be 20cm. This recommendation can be taken into account in the development of monitoring techniques for implementation in the context of REDD+.

Fabaceae-Caesalpinioideae had the highest above-ground biomass, estimated at 24.24% in Bidou and 29.14% in Campo respectively and a comparatively low value (4.11%) at the Mangombe station. In the Guyana forest, the same family is dominant and constitutes more than a third of the biomass. Within this area, 92.93% of the biomass consists of 15 families, represented in the following decreasing order: Caesalpinioideae (36.54%), Lecythidaceae (9.81%), Caryocaraceae (7.91%), Humiriaceae (7.54%), Lauraceae (7.54%), and Moraceae (4.41%) (Lescure *et al.*, 1983). In the Dja forest of Cameroon, Djuikouo *et al.*, (2010) observed that *Gilbertiodendron dewevrei*, which is a Fabaceae, accounts for 83% of the above-ground biomass, while *Pentaclethra macrophylla* Benth. (Fabaceae-Mimosoideae) is dominant in the heterogeneous forests (9.9%) and *Uapaca heudelotii* Baill. (Euphorbiaceae) represents 10.6% in the periodically flooded forests.

Variation of root and litter biomass

Research on root biomass has been extensively conducted in the temperate environment with little information available in the tropical rainforest. Data from extant literature indicates that tropical forest root biomass ranges from 4.5 to 92.5t/ha, higher than the values (0.5 - 13t/ha) obtained in temperate forests (Noij *et al.*, 1993). In this study, root biomass ranged from 19.01t/ha (Campo) to 26.06t/ha (Bidou) with a significant advantage in the secondary forest. These values remain within the data range from different areas that show tropical forest root biomass values stretching from 14.4 to 40t/ha, with exceptions for Brazil and Surinam where they are more significant. Fine roots account for about 30% of belowground biomass and are regularly concentrated in the upper parts of the soil (Grier *et al.* 1981). We found in all sites that root biomass decreases with depth and more than 63% of fine root biomass is concentrated in the upper soil layer (0 – 20cm). This result is similar to Fortier *et al.* (2011) who found 61 to 78% of fine root biomass accumulated in the 0 - 20cm layer in the Canadian forest. Castellanos *et al.* (2001) and Ibrahima *et al.* (2002) also realized 70% within 5cm depth in the tropical forest.

In general, estimating the biomass of roots is a challenging exercise due to difficulties related to sampling, soil structure, texture, as well as problems in dissociating the dead from living roots, since the production and mortality of fine roots is simultaneous. Many factors can influence root biomass such as age of tree and vegetation, season, altitude, soil structure, texture, and according to some authors (Leuschner *et al.*, 2007; Graefe *et al.*, 2008), abiotic factors like water and nutrient availability. Other authors (Yavitt and Wright, 2001; Zobel *et al.*, 2007) agree that temperature can favour fine root production even if the results are controversial.

Regarding litter biomass, it varies according to tree phenology, wind speed, season and the organic matter decomposition process. The value of litter biomass ranged between 4.02t/ha to 7.10t/ha in all the sites. This represented only 1% of the total biomass of each site. These values are comparable to those obtained by Sishir *et al.* (2012) in the tropical forest (5.6t/ha in the dry season and 20.6t/ha in the rainy season with an average of 14t/ha which represented 1.8% total biomass). According to Clark *et al.* (2001), it varies from 1.8-18.6t/ha. This information shows that the contribution of litter to forest biomass can be neglected.

Conclusion

Above and below ground biomass in Mangombe, Bidou and Campo forest stations in the rainforest of Cameroon decrease with increase in the level of disturbance. The aboveground biomass observed in intact mature forest of Campo is sometimes 4 times higher than values known for tropical forests, suggesting that this forest station is an important reservoir for carbon.

These high biomass values can be explained by the species richness, variability of tree architecture (size and height), heterogeneity of forest types and the level of disturbance. The results of this study however have the weakness of being confined to a limited space. The variability of biomass values observed in the different inventoried plots, as well as other sites of the Congo Basin, highlights the need to increase the study area, the importance of standardization of data collection methods and the development of reasonably reliable biomass prediction equations for the Congo Basin forests.

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